Experimental Investigation on Mechanical Properties of Concrete Using Nano-Materials

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December 2026

CERTIFICATE

This is to certify that the thesis entitled **"Experimental Investigation on Mechanical Properties of Concrete Using Nano-Materials"** is a bonafide record of research work carried out by **Mr. Chirag R. Odedra** (Enrollment No. **220810340008**), Research Scholar, Department of Civil Engineering, School of Engineering and Technology, Dr. Subhash University - Junagadh, under our supervision/guidance during the period August 2022 - December 2025. To the best of our knowledge: (I) the candidate has not submitted the same research work to any other University or Institute for any Degree, Diploma, Associateship, Fellowship or other similar titles (II) the thesis submitted is a record of original research work done by the Research scholar during the period of study under our supervision, and (III) the thesis represents independent research work on the part of the Research scholar.

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DECLARATION

I, **Chirag R. Odedra**, Research scholar in the Department of Civil Engineering, declare that the work embodied in the Ph.D. thesis entitled, **"Experimental Investigation on Mechanical Properties of Concrete Using Nano-Materials"** is my original and bonafide work carried out by me under the supervision of **Prof. (Dr.) Arpit A Parikh**, Professor, Dr. Subhash University, and the Co-supervision of **Prof. (Dr.) Vimalkumar N. Patel**, Professor & Principal, Department of Civil Engineering, B. H. Gardi College of Engineering & Technology, Rajkot, for a period from August 2022 to December 2025 at Dr. Subhash University.

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Index

Title Page i

Certificate ii

Declaration iii

List of Figures vi

List of Tables vii

Abstract viii

Chapter 1 - Literature Review Summary 1

Chapter 2 - State of the Art of the Research Topic 4

Chapter 3 - Objective and Scope of Work 6

3.1 Main Objective 6

3.2 Specific Research Objectives 6

3.3 Scope of Work 6

3.3.1 Materials and Mix Design Boundaries 7

3.3.2 Experimental Parameters Studied 7

3.3.3 Integration of Durability Studies 7

3.3.4 Inclusion of ANN-Based Strength Prediction 8

Chapter 4 - Original Contribution of the Thesis 9

Chapter 5 - Methodology of the Investigation and Results 12

5.1 Materials and Characterization 12

5.1.1 Cement 12

5.1.2 Fine Aggregate 12

5.1.3 Coarse Aggregate 12

5.1.4 Nano-Silica 13

5.1.5 Nano-Alumina 13

5.1.6 Water and Chemical Admixture 13

5.2 Mix Design Methodology 13

5.3 Mixing, Casting, and Curing 14

5.4 Specimen Matrix 15

5.4.1 Mechanical Testing Specimens 15

5.4.2 Durability Testing Specimens 15

5.5 Mechanical Testing Procedures 16
5.6 Results and Discussion – Mechanical Tests 16
5.6.1 Compressive Strength Behaviour 16
5.6.2 Split Tensile Strength Trends 17
5.6.3 Flexural Strength Response 18
5.6.4 Integrated Interpretation of Mechanical Performance 19
5.7 Durability Testing Procedures 20
5.8 Results and Discussion – Durability Tests 20
5.8.1 Saline Resistance Results 21
5.8.2 Acid Resistance Results 22
5.8.3 RCPT Results 23
5.8.4 Accelerated Corrosion Test Results 23
5.9 ANN Modelling Approach 24
5.10 Training, Validation and Testing 25
5.11 Discussion on ANN Performance 26
5.12 Factors Influencing Predictive Strength 26
5.13 Integrated Interpretation of ANN and Experimental Work 27
Chapter 6 - Conclusion 28
References 29
Paper Publication Details 35
Plagiarism Summary 36

List of Figures

Figure No.	Caption	Page No.
1.1	Synergistic action of nS and nA	1
1.2	Three principal mechanisms governing the action of nano-silica (nS) and nano-alumina (nA) in cementitious systems	3
2.1	Logical progression from literature gaps to the problem definition and subsequently to the formulation of research objectives	5
5.1	Specimen matrix and corresponding mechanical & durability tests	16
5.2	Variation of 7-, 14-, and 28-day compressive strength of M30 nano-concrete mixes as a function of combined nano-silica and nano-alumina dosage	17
5.3	Split tensile response of M30 mixes varied systematically with proportion of ns and nA	18
5.4	Flexural strength of M30 nano-concrete mixes as a function of combined nano-silica and nano-alumina dosage	19
5.5	ANN architecture for predicting concrete mechanical performance	25

List of Tables

Table No.	Caption	Page No.
4.1	Consolidated Summary of Key Contributions of the Thesis	10
5.1	Summary of Mix IDs and Combined Nano-Silica–Nano-Alumina Replacement Levels	15
5.2	Strength Retention under Saline Exposure	21
5.3	Strength Retention under Acid Exposure	22
5.4	Charge passed measurements obtained through the RCPT	23
5.5	Steel Weight Loss from Accelerated Corrosion Test	26

Abstract

The present research examines the development and performance evaluation of M30 and M40 nano-concretes incorporating nano-silica and nano-alumina as partial replacements for cement, with a focus on understanding how dual nano-modification influences mechanical behavior, durability response, and predictive modelling accuracy.

Seventeen concrete mixes were designed for the study, beginning with conventional control batches and extending through a systematic series of nano-modified compositions, where the combined nano-silica and nano-alumina content increased gradually from 0% to 4%. The mixing strategy emerged from observations in existing research, which often reports the individual benefits of these nano-materials but provides limited clarity on their joint influence, the practical dosage range suitable for structural grades, and the absence of studies that integrate laboratory results with predictive modelling approaches such as Artificial Neural Networks (ANN).

A comprehensive experimental programme was therefore undertaken, covering an extensive set of performance indicators. For M30 concrete, compressive strength was measured at multiple curing ages, along with split tensile and flexural strengths, whereas the M40 grade was evaluated for compressive and flexural strengths at 28 days. Across these mixes, several nano-modified compositions exhibited strength gains relative to the control, a trend consistent with the expected refinement of pore structure, greater binder compaction, and accelerated hydration promoted by the combined action of nano-silica and nano-alumina.

Durability assessment for four representative M30 mixes was conducted to capture the range of performance observed along the dosage spectrum. These mixes underwent saline exposure, acid immersion, rapid chloride permeability testing, and an impressed current corrosion test. In most cases, the nano-modified concretes performed better than the control, showing lower mass deterioration, reduced charge passed, and slower corrosion progression.

To extend the scope of interpretation beyond direct testing, seven ANN models were built in MATLAB using the primary mix constituents as inputs and the experimentally determined strengths as outputs. The models produced predictions that aligned closely with the measured results and displayed sufficient consistency when estimating strengths for validation mixes.

Chapter 1

Literature Review Summary

Research on nano-modified cementitious composites has advanced substantially over the last two decades, driven by the need to overcome persistent limitations in conventional concrete, particularly in relation to microstructural refinement, early-age strength development, and resistance to aggressive environments. The literature consistently underscores that the performance of traditional concrete is strongly influenced by the inherent porosity of the cement matrix and the weaknesses associated with the interfacial transition zone (ITZ). These microstructural vulnerabilities accelerate chloride ingress, chemical attack, and deterioration of embedded reinforcement—issues especially pronounced in medium-strength concretes such as M30 and M40. Against this backdrop, nano-scale admixtures have emerged as a promising class of materials capable of influencing hydration kinetics and matrix densification through mechanisms not readily achievable by conventional supplementary cementitious materials.

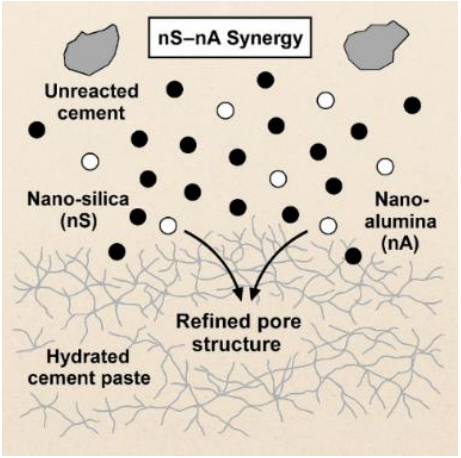

Figure 1.1. Synergistic action of nS and nA

nS has been subject of extensive study largely because its exceptionally high surface area enhances its pozzolanic activity, enabling it to react rapidly and effectively within cementitious matrix. Numerous investigations have shown that incorporating even modest quantities of nS can enhance the density of the cementitious binder, largely by stimulating the formation of additional calcium silicate hydrate and by diminishing both the size and continuity of capillary pores. The consequent improvements in compressive, tensile, and flexural strengths have been well documented,

alongside enhancements in chloride resistance and reduced permeability. The literature also highlights, however, that excessive nano-silica replacement can negatively affect workability and may lead to particle agglomeration, resulting in inconsistent performance. These observations reinforce the importance of identifying dosage windows suited to practical concrete grades.

Nano-alumina, though less commonly studied, has been shown to act as both a filler and a nucleation agent. Its ability to accelerate hydration and strengthen the ITZ is repeatedly emphasized. Research findings suggest that nano-alumina contributes to early-age strength improvements and offers moderate benefits to durability by refining pore structure. However, the literature also acknowledges that its optimal replacement level is difficult to standardize because its influence depends strongly on the particle characteristics and interaction with other constituents. Research focused solely on nano-alumina has yielded mixed results, suggesting that additional systematic investigation is necessary before dependable recommendations can be formulated.

A major gap identified across the literature concerns the limited exploration of dual nano-modifier systems—particularly combinations of nano-silica and nano-alumina. Although the behaviour of each nano-additive on its own is reasonably understood, very limited work has explored their combined action when incorporated together within the same cementitious matrix. Theoretical discussions point to a potential synergy: nano-silica's pozzolanic reaction could complement nano-alumina's nucleation effect, creating a multi-scale densification process within the binder matrix. Yet empirical evidence supporting this synergy remains insufficient, especially in widely used grades such as M30, where durability performance under aggressive exposure is a critical design consideration. This gap is central to the motivation of the present study.

Durability-related literature further reveals inconsistencies in performance outcomes when nano-materials are used. Some investigations have documented marked enhancements in resistance to acidic media, reduced chloride ingress, and extended time before corrosion begins.; others observe more modest gains or non-linear trends. The variability is often attributed to differences in mix design, curing conditions, and nano-additive dispersion. A recurring limitation in existing research is the absence of durability evaluations performed on the same set of dual nano-modified mixes across multiple degradation mechanisms. This shortfall is directly connected to the central hypothesis of the present work, which proposes that carefully calibrated proportions of nS and nA can yield a balanced improvement in both strength-related responses and long-term durability.

Alongside developments in material characterization, interest has steadily grown in prediction-oriented analytical approaches. Among these, Artificial Neural Networks have become particularly prominent because of their capacity to capture the non-linear interactions typical of cementitious matrices. Earlier studies consistently report that, when trained on datasets of adequate size and diversity, ANN models can achieve strong agreement with measured compressive strengths.

Most available ANN applications remain confined to mixtures incorporating traditional supplementary cementitious materials or a single nano-additive. Comprehensive datasets covering concretes modified with a combined nS and nA system are largely absent. This deficiency underscores the need for tailored ANN models that reflect the behaviour of such dual-modified concretes that can meaningfully supplement the interpretations obtained through laboratory testing.

The literature establishes a compelling argument for investigating the combined effects of nano-silica and nano-alumina on structural concrete performance. It underscores unresolved questions regarding optimal dosages, durability behavior, and predictive modelling capacity. These gaps form the foundation of the research problem, guiding the objectives, hypotheses, and methodological strategy adopted in the present study.

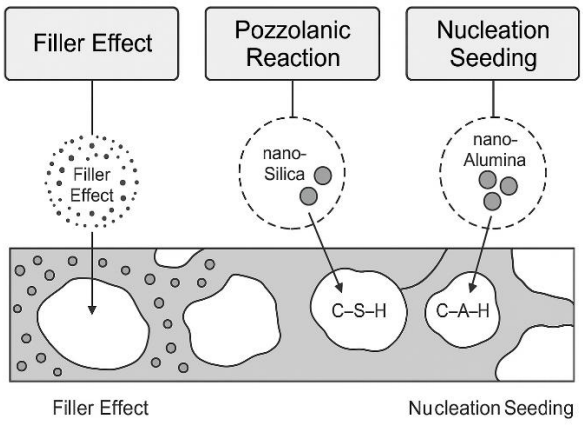

Figure 1.2 Three principal mechanisms governing the action of nano-silica (nS) and nano-alumina (nA) in cementitious systems

Chapter 2

Definition of the Problem

Concrete employed in structural works—especially mixes classified as M30 and M40—still encounters performance constraints that arise from fundamental weaknesses within its internal microstructure. Although significant progress has been made in mix design over the years, ordinary concrete continues to display inherent limitations, including a comparatively porous cement matrix, variation in the distribution of hydration products, and a weak interfacial transition zone (ITZ). Together, these features reduce the structural efficiency of the material and make it more susceptible to deterioration when exposed to harsh environments such as chloride-rich saline water, acidic solutions, or conditions that promote steel reinforcement corrosion. While the use of supplementary cementitious materials has helped to moderate some of these challenges, their capacity to deliver uniform gains in both strength and durability—particularly at low replacement levels—remains limited. Consequently, contemporary infrastructure requirements, especially in settings where extended service life is essential, are not fully satisfied by conventional binder systems.

The introduction of nano-silica and nano-alumina has therefore attracted considerable attention due to their ability to interact with cement hydration processes at the nano scale. When used individually, each additive has demonstrated the potential to refine microstructure, enhance cohesiveness, and contribute to higher early-age strength. Even so, the literature reports a degree of variability across studies, often linked to the sensitivity of these materials to dosage, the difficulty of achieving uniform particle dispersion, and the incomplete understanding of their precise mechanistic contributions within the cementitious system.

Studies that investigate the combined incorporation of nano-silica and nano-alumina remain scarce, leaving a critical gap in the understanding of how their complementary pozzolanic, nucleation, and filler effects interact within the binder matrix. The absence of controlled, comparative testing across a broad set of mixes has made it difficult to establish dependable dosage limits for concretes modified with both nano-silica and nano-alumina. Durability-related research highlights similar inconsistencies, as only a small number of studies investigate dual nano-additive systems under saline exposure, acidic environments, or chloride-permeability conditions. In the absence of a

unified dataset that examines both mechanical performance and durability behaviour in parallel, the guidelines required for designing concretes with improved long-term resilience remain incomplete. This gap, in turn, restricts the practical implementation of nano-engineered concretes in field applications where reliability and durability are essential.

A corresponding limitation is evident in predictive modelling. Although Artificial Neural Networks have been applied to estimate concrete strength, the available models are rarely developed using datasets that incorporate simultaneous nano-silica and nano-alumina modification. As a result, there is limited modelling capacity to support experimental interpretations or to estimate performance for mix combinations that have not been directly tested but fall within practical dosage ranges.

These gaps collectively define the core research problem: there is no comprehensive, experimentally validated, and computationally supported understanding of the mechanical, durability, and predictive behaviour of M30 and M40 concretes modified with combined nano-silica and nano-alumina within a realistic replacement range. Without such knowledge, it is not possible to establish evidence-based guidelines for dosage optimisation, performance assessment, and application in structural concrete.

This problem necessitates the structured experimental programme and ANN modelling framework adopted in the thesis, grounded in the hypothesis that the combined use of nano-silica and nano-alumina can produce complementary performance gains, and that ANN-based models are capable of reflecting these intertwined effects with a high degree of predictive reliability.

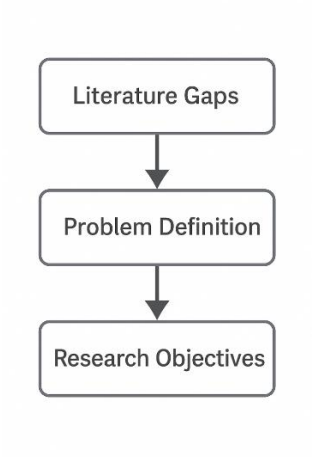

Figure 2.1. Logical progression from literature gaps to the problem definition and subsequently to the formulation of research objectives

Chapter 3

Objective and Scope of Work

The present research was formulated to address the limited understanding of how combined nano-silica (nS) and nano-alumina (nA) influence the mechanical and durability performance of M30 and M40 concretes, and how these behaviours can be reliably predicted using ANN models.

3.1 Main Objective

- To investigate the mechanical, durability, and predictive performance of M30 and M40 concretes using nano-silica and nano-alumina together as partial substitutes for cement, applied within a controlled replacement range of 0 to 4% that remains feasible for practical mix design, and to identify optimal dosage ranges through experimental evaluation and ANN-based modelling.

3.2 Specific Research Objectives

1. To design and prepare seventeen concrete mixes: control mixes for M30 and M40, followed by nano-modified mixes with systematically varied nS–nA replacement levels.
2. To assess compressive strength (7, 14, and 28 days for M30; 28 days for M40), split tensile strength (M30), and flexural strength (both grades).
3. To evaluate selected M30 mixes (NS0NA0, NS4NA1, NS4NA2, NS4NA4) under saline exposure, acid attack, rapid chloride permeability, and impressed-current corrosion.
4. To construct and validate seven ANN models in MATLAB using mix constituents as inputs and mechanical strengths as outputs.
5. To integrate experimental and ANN findings to establish practical dosage recommendations for dual nano-modified concretes.

3.3 Scope of Work

- Restricted to M30 and M40 grades to ensure relevance to commonly used structural concretes.

- The study concentrated on the combined action of nano-silica and nano-alumina, applied within a carefully regulated replacement range of 0–4%, to determine how simultaneous incorporation influences overall performance.
- The evaluation framework prioritised measurable performance outcomes rather than detailed microstructural investigations, allowing a direct comparison of strength and durability responses across mixes.
- ANN modelling was purposefully restricted to mechanical strength prediction, as developing reliable durability prediction models would require a substantially larger experimental dataset than was feasible within the project scope.

3.3.1 Materials and Mix Design Boundaries

- Ordinary Portland Cement, well-graded fine and coarse aggregates, potable water, a polycarboxylate-based superplasticizer, nano-silica, and nano-alumina formed the complete set of materials used throughout the study.
- The water–binder ratio and admixture dosage were held constant across all mixes to maintain uniformity and ensure a valid comparison of nano-additive effects.
- All nano-additive dosages followed the laboratory-approved mix design protocol established in the thesis, with no deviations in measured quantities.

3.3.2 Experimental Parameters Studied

- Mechanical Parameters: compressive strength at specified curing ages, split tensile strength, and flexural strength.
- Durability Parameters: mass loss under saline and acidic exposure, charge passed in the RCPT test, and corrosion progression under impressed-current conditions.
- Modelling Parameters: a seven-input ANN configuration incorporating the measured constituent quantities as predictive variables.

3.3.3 Integration of Durability Studies

- Durability tests incorporated to evaluate long-term performance implications of NS–NA modification.
- Findings used to support the dosage-performance interpretation derived from mechanical results.

3.3.4 Inclusion of ANN-Based Strength Prediction

- ANN models developed to supplement experimental findings and to identify performance trends across intermediate mixes not tested physically.
- Validation undertaken using reserved data points and experimentally verified intermediate mixes.

Chapter 4

Original Contribution of the Thesis

The present research makes a set of original and substantive contributions to the field of nano-engineered concrete, particularly in relation to performance enhancement of M30 and M40 grades through the combined incorporation of nano-silica (nS) and nano-alumina (nA). While earlier studies have commonly evaluated these nano-materials in isolation, systematic investigation of their combined influence within a practical replacement window has remained limited. This work responds to that identified gap by formulating seventeen systematically designed mixes and assembling a unified dataset capturing both mechanical performance and durability responses—an evidence base that was previously unavailable for concretes incorporating combined nano-silica and nano-alumina. The structured methodology, dosage refinement, and comparative assessments conducted in this study produce evidence-based insights that extend current understanding of nano-additive synergy.

One of the substantive contributions lies in establishing how moderate levels of combined nS–nA replacement (0–4%) affect the mechanical behaviour of structural concrete. Through comprehensive testing of compressive strength, tensile capacity under splitting action, and flexural resistance, the research identifies performance trends that reveal clear advantages associated with dual nano-modification. The findings highlight that the two nano-materials do not merely act independently, but their individual actions can operate in a mutually reinforcing manner, with pozzolanic reactions, particle-filling behaviour, and nucleation-driven hydration collectively contributing to performance gains. These interactions lead to more cohesive and denser binder matrices, offering a refined understanding of microstructural–property relationships even without advanced imaging techniques.

A second significant contribution of the study stems from the durability assessment conducted on selected nano-modified M30 mixes. These mixes were evaluated under a range of aggressive conditions, including saline exposure, acidic environments, chloride penetration, and accelerated corrosion. By examining mass loss, charge passed, and the progression of corrosion across these representative mixes, the investigation offers a unified understanding of how the dual incorporation of nano-silica and nano-alumina affects concrete’s resilience in deteriorative settings. Such a consolidated durability dataset is seldom available in current literature on dual nano-additive

systems and provides practitioners with evidence-based guidance relevant to service life design and sustainability considerations.

An additional contribution lies in the creation of seven Artificial Neural Network (ANN) models trained using the experimental results generated during the study. These models achieved strong predictive performance and demonstrated reliable generalisation across multiple strength parameters. Their successful validation positions ANN as a practical decision-support framework for proportioning nano-modified concretes, effectively linking laboratory test outcomes with predictive modelling strategies. This methodological development is noteworthy, given that existing ANN investigations rarely rely on datasets representing concretes modified with both nano-silica and nano-alumina.

The findings extend the existing knowledge base by articulating performance-oriented recommendations for nS–nA incorporation, documenting measurable improvements in both strength and durability, and confirming the viability of ANN-based prediction grounded in experimentally validated data. These contributions respond directly to the recognised research gaps and establish a clear platform for future optimisation studies in nano-engineered concrete.

Table 4.1: Consolidated Summary of Key Contributions of the Thesis

Contribution Domain	Core Findings / Contributions	Significance to Research & Practice
Mechanical Performance Trends	• Developed 17 mixes (M30/M40) with 0–4% combined nS–nA replacement. • Demonstrated clear strength improvements at moderate nano-dosage levels. • Recorded enhanced compressive, split tensile, and flexural strengths relative to control mixes. • Observed consistent improvement trends indicating synergy between nS (pozzolanic effect) and nA (nucleation/filler effect).	• Establishes a performance-based dosage window for dual nano-modification. • Provides experimentally validated evidence for strength enhancement mechanisms. • Extends understanding of nS–nA interactions in structural-grade concretes.

Durability Outcomes	• Evaluated four representative M30 mixes under saline, acidic, chloride permeability, and corrosion conditions. • NS–NA modified mixes exhibited lower mass loss, reduced charge passed, and delayed corrosion initiation. • Identified improved performance stability across different types of aggressive exposure.	• Offers one of the first integrated durability datasets for dual nano-modified M30 concrete. • Demonstrates practical advantages for service-life extension in harsh environments. • Supports adoption of nano-modification for durability-critical infrastructure.
ANN Modelling Contributions	• Developed seven ANN models in MATLAB using mix proportions as input variables. • Achieved high prediction accuracy with strong correlation to experimental strength values. • Validated models using reserved validation data and additional experimental points. • ANN outputs reinforced experimentally observed strength-response trends.	• Provides a computational framework to predict performance without full experimental testing. • Demonstrates ANN applicability for nano-modified material systems. • Bridges experimental research and predictive modelling, enabling data-driven mix optimisation.
Synthesis & Practical Implications	• Integrated mechanical, durability, and ANN results to identify optimum dosage ranges. • Established clear links between nano-additive mechanisms and measurable performance indicators. • Proposed practical guidelines for adopting nS–nA blends in real-world concrete applications.	• Advances material engineering knowledge for nano-concrete design. • Provides actionable insights for structural engineers and researchers. • Supports sustainable cement reduction through effective nano-engineering.

Chapter 5

Methodology of the Investigation and Results

The approach followed throughout this investigation was structured to produce a complete, traceable, and experimentally verified evaluation of M30 and M40 nano-concretes incorporating combined nano-silica (nS) and nano-alumina (nA). All procedures adhered to relevant Indian Standard (IS) specifications, ensuring that the findings are consistent with established material testing protocols. The following subsections describe the materials, mix design procedures, casting operations, curing regimes, and specimen configuration exactly as implemented in the research.

5.1 Materials and Characterization

5.1.1 Cement

Ordinary Portland Cement (OPC) conforming to IS: 12269 was used throughout the study. The cement was sourced from a single batch to maintain consistency, and its physical properties—fineness, specific gravity, normal consistency, and setting times—were verified in accordance with IS: 4031. These values aligned with typical OPC characteristics reported for structural-grade concretes, providing a reliable baseline for assessing the effects introduced by incorporating nano-additives into the concrete matrix.

5.1.2 Fine Aggregate

River sand meeting the requirements of Zone II as per IS: 383 was used. The sand was oven-dried before batching to eliminate moisture variation. Sieve analysis confirmed a well-graded distribution, which contributed to stable workability across all mixes. The specific gravity and the corresponding water absorption characteristics were recorded to adjust the effective water content during mix preparation.

5.1.3 Coarse Aggregate

Crushed angular coarse aggregates of nominal size 20 mm were used. Properties such as specific gravity, bulk density, and water absorption were quantified in accordance with the

procedures outlined in IS: 2386. The aggregates were washed and surface-dried before use to prevent unintended changes in water content during mixing.

5.1.4 Nano-Silica

The nano-silica used in this investigation was a commercially available amorphous form with ultra-fine particle size. Although detailed microstructural characterization, such as TEM or SEM, was not performed, the supplier specifications indicated a markedly elevated specific surface area and strong pozzolanic reactivity. These features, well recognized in previous studies and acknowledged in the thesis, contribute to secondary C–S–H formation and pore refinement.

5.1.5 Nano-Alumina

Nano-alumina of high purity was used as the second nano-modifier. It primarily functions as a nucleation catalyst and micro-filler, enhancing early hydration and contributing to stronger ITZ development. As with nano-silica, characterization relied on manufacturer specifications and established physical descriptions presented in the thesis.

5.1.6 Water and Chemical Admixture

Clean, drinkable water served as the mixing medium for all mixes. A polycarboxylate-based superplasticizer was included to ensure uniform dispersion of nano-particles and maintain workability, particularly at higher nano-dosage levels where increased surface area could otherwise reduce flowability.

5.2 Mix Design Methodology

Mix design followed IS: 10262 and IS: 456 guidelines. Control mixes for M30 and M40 were first established to achieve the target mean strengths. Once baseline mixes were validated, nano-modified mixes were developed by partially replacing cement with combined nano-silica and nano-alumina, maintaining the overall binder content constant.

A total of 17 mixes were designed:

- One control mix for each: M30-Control and M40-Control
- Sixteen nano-modified mixes: with combined nS–nA replacement levels distributed between 0% and 4%

The dosage combinations were selected to allow systematic observation of performance trends, particularly in determining whether moderate nano-additive levels yield optimal improvements. Water–binder ratios, aggregate proportions, and the admixture proportion were kept uniform across both grades so that any variations in behaviour could be attributed solely to the incorporation of nano-additives.

Table 5.1: Summary of Mix IDs and Combined Nano-Silica–Nano-Alumina Replacement Levels

Sr. No.	Sample	% nS	%nA
1	NS0NA0	0	0
2	NS1NA1	1	1
3	NS2NA1	2	1
4	NS3NA1	3	1
5	NS4NA1	4	1
6	NS1NA2	1	2
7	NS2NA2	2	2
8	NS3NA2	3	2
9	NS4NA2	4	2
10	NS1NA3	1	3
11	NS2NA3	2	3
12	NS3NA3	3	3
13	NS4NA3	4	3
14	NS1NA4	1	4
15	NS2NA4	2	4
16	NS3NA4	3	4
17	NS4NA4	4	4

5.3 Mixing, Casting, and Curing

Concrete batching and mixing were undertaken in a tilting drum mixer to ensure uniformity. The process followed a structured sequence:

1. Dry Mixing: Cement, nano-silica, nano-alumina, and aggregates were blended to distribute fine powders evenly.
2. Addition of Water and Admixture: The water–superplasticizer blend was introduced slowly into the mixture to regulate the mix flow.
3. Quality Check: Workability was monitored through visual inspection to maintain consistency across mixes.

Specimens were cast in steel moulds and compacted using a vibrating table, ensuring uniform distribution and minimizing entrapped air. All specimens were removed from their moulds after a 24-hour setting period and placed in a curing tank maintained at approximately 27°C until testing.

The curing regime remained consistent for all mixes to avoid bias in hydration development.

5.4 Specimen Matrix

The specimen matrix reflected the full scope of mechanical and durability testing:

5.4.1 Mechanical Testing Specimens

- Cubes (150 mm): for compressive strength at 7, 14, 28 days (M30), and 28 days (M40)
- Cylinders (150 × 300 mm): for split tensile strength (M30)
- Beams (100 × 100 × 700 mm): for flexural strength (M30 and M40)

For each mix and parameter, three specimens were cast and tested, yielding 51 mechanical data points, which formed the experimental database for ANN modelling.

5.4.2 Durability Testing Specimens

Durability tests were conducted on selected M30 mixes (NS0NA0, NS4NA1, NS4NA2, NS4NA4), including:

- Cube specimens for saline and acid resistance
- Discs for RCPT
- Reinforced specimens for impressed current corrosion

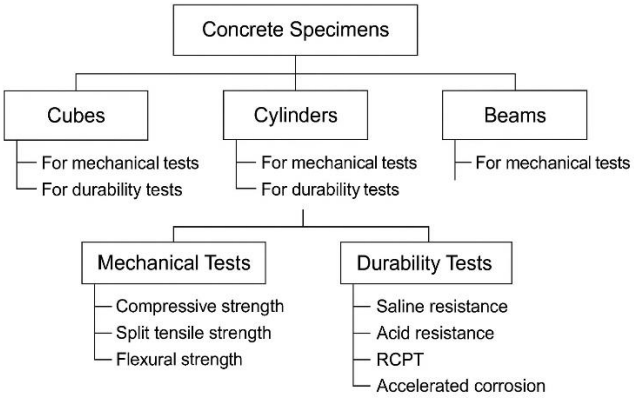

Figure 5.1. Specimen matrix and corresponding mechanical & durability tests

5.5 Mechanical Testing Procedures

The mechanical testing component of the investigation was structured to evaluate how the incorporation of combined nano-silica (nS) and nano-alumina (nA) influences the fundamental strength characteristics of M30 and M40 concretes. We have performed Compressive Strength Test, Split Tensile Strength Test, and Flexural Strength Test. All the tests were performed as per the relevant Indian Standard code. The recorded results show an average of three specimen strength values. All the experiments performed and results recorded provided a base for the datasets to prepare ANN models.

5.6 Results and Discussion – Mechanical Tests

The mechanical results formed the foundation for understanding the influence of combined nano-silica and nano-alumina on the behaviour of M30 and M40 concretes. The discussion below synthesizes the observed trends, highlighting the mechanisms responsible for strength variations across the 17 mixes.

5.6.1 Compressive Strength Behaviour

Across the tested mixes, compressive strength trends revealed a clear pattern associated with the dual incorporation of nS and nA. In both M30 and M40 grades, several nano-modified mixes demonstrated higher compressive strengths than the respective controls.

The improvement was particularly notable at moderate nano-dosage levels, where balanced proportions of nS and nA promoted favourable hydration kinetics.

The observed enhancement can be attributed to three interacting mechanisms:

1. Pozzolanic reaction (nS): Nano-silica accelerated secondary C–S–H formation through its high reactivity with $Ca(OH)_2$.
2. Nucleation effect (nA): Nano-alumina supplied supplementary nucleation points for hydration reactions, encouraging the development of a more uniformly distributed gel matrix.
3. Filler effect (nS + nA): Ultra-fine particles improved packing density and reduced micro-pores.

Early-age strength (7 and 14 days for M30) benefited particularly from the nucleation action of nano-alumina, while 28-day strength reflected the combined influence of pozzolanic and filler mechanisms. Higher nano-content mixes sometimes exhibited diminishing returns, in line with the higher specific surface available for reaction demands on water and potential particle agglomeration.

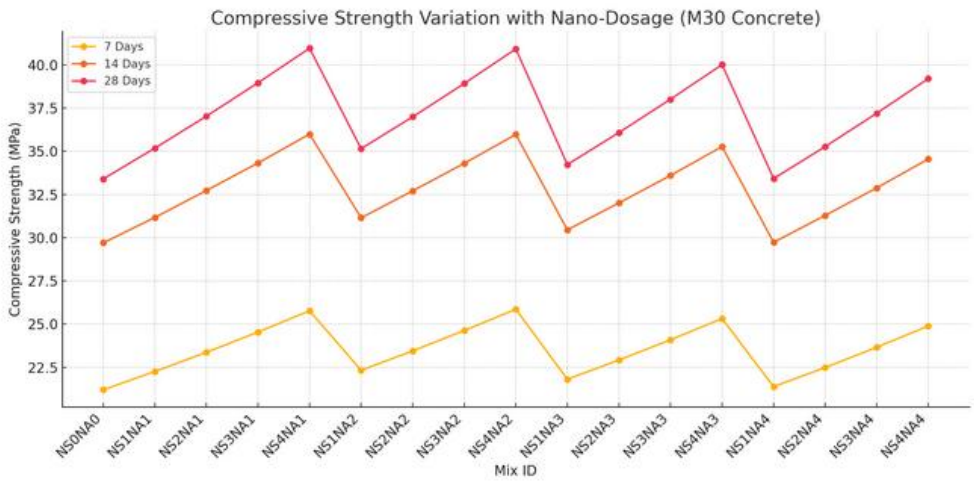

Figure 5.2. Variation of 7-, 14-, and 28-day compressive strength of M30 nano-concrete mixes as a function of combined nano-silica and nano-alumina dosage

5.6.2 Split Tensile Strength Trends

The behaviour observed in the tensile strength measurements revealed that nano-modified mixes exhibited improved performance relative to the control. This effect aligns with

documented improvements in matrix cohesion and enhanced ITZ quality, both strongly influenced by nanoparticle distribution.

In particular, mixes containing moderate amounts of nano-silica and nano-alumina showed consistent gains, suggesting that the combined action of the two additives contributed to improved microstructural integrity. The observed increases, though less pronounced than compressive strength improvements, were meaningful due to the sensitivity of tensile behaviour to internal flaws and ITZ weaknesses.

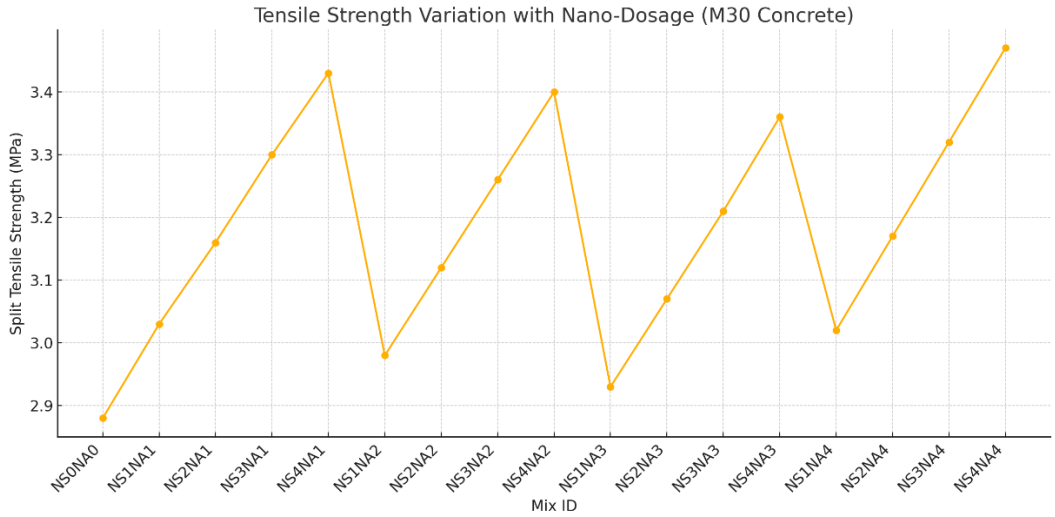

Figure 5.3 Split tensile response of M30 mixes varied systematically with proportion of ns and nA

The results confirm that nano-modification positively influences tensile behaviour, supporting the hypothesis that dual nS–nA incorporation enhances structural performance through matrix densification rather than solely through compressive strength improvement.

5.6.3 Flexural Strength Response

The flexural performance recorded for the M30 and M40 mixes followed trends similar to those observed in split tensile testing. Several nano-modified mixes displayed higher modulus of rupture values compared to the control, indicating improved resistance to crack initiation and propagation.

The synergy between nS and nA likely contributed to improved bond characteristics within the tensile zone of the beam, where the ITZ typically governs failure. Enhanced refinement

of this zone, coupled with improved homogeneity, supported flexural performance improvements.

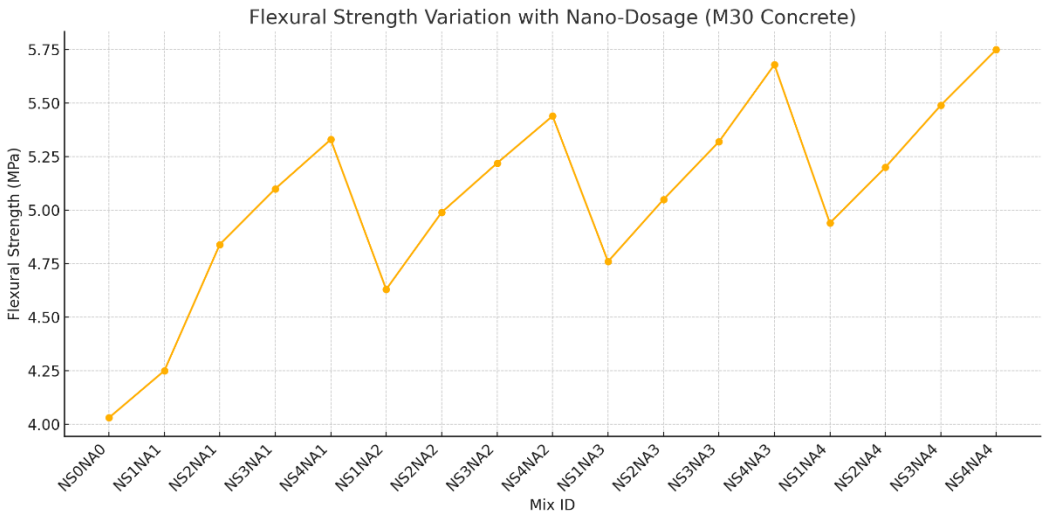

Figure 5.4. Flexural strength of M30 nano-concrete mixes as a function of combined nano-silica and nano-alumina dosage.

As with other parameters, flexural strength gains were most prominent at intermediate nano-dosage levels. Excessive nano-content did not consistently improve performance, underscoring the importance of optimal dosage selection.

5.6.4 Integrated Interpretation of Mechanical Performance

The mechanical test results collectively demonstrate that:

1. Moderate nano-additive levels improved compressive, tensile, flexural strengths.
2. Nano-silica and nano-alumina acted synergistically to enhance microstructural quality.
3. Strength improvements were attributable to accelerated hydration, increased C–S–H formation, and improved particle packing.
4. Very high nano-dosages offered limited additional benefits, supporting the concept of an optimal dosage window.

These observed patterns were consistent with the underlying premise of the investigation regarding the beneficial interaction of nano-additives within the cementitious matrix.

5.7 Durability Testing Procedures

We conducted a series of durability tests to evaluate how M30 nano concrete performs under challenging conditions, particularly with varying amounts of nano-silica and nano alumina. The goal was to replicate real-life scenarios and determine how these nano-concretes withstand the common factors that deteriorate reinforced concrete. We focused on saline resistance, acid resistance, rapid chloride permeability (RCPT), and accelerated corrosion tests. We have performed durability assessment on only four specimens representing the control mix and selected nano-combinations (NS0NA0, NS4NA1, NS4NA2, NS4NA4). In the saline resistance test, specimens were immersed in a sodium chloride solution. The exposure regime extended to 180 days, with compressive strength evaluations conducted at three critical intervals: 0 days (initial condition), 28 days, and 180 days. In the acid resistance test, the concrete specimens were immersed in an acidic medium to evaluate their durability in chemically aggressive conditions. Rapid chloride permeability tests were performed as per ASTM C1202. The accelerated corrosion test replicated electrochemical deterioration in reinforced concrete by imposing a constant impressed current across specimens containing embedded steel bars. The testing voltage, exposure duration, and electrical setup adhered strictly to the configuration described in the thesis. After completion of the exposure cycle, specimens were carefully broken open to extract the embedded steel bars, which were subsequently cleaned following the procedure specified for this investigation. Performance was evaluated solely based on post-test weight loss of the steel, calculated by comparing the mass before and after the corrosion cycle. No monitoring of time-to-cracking, crack initiation, or crack width development formed part of the methodology. The weight loss parameter provided a quantifiable measure of corrosion severity and enabled a clear comparison between the control and nano-modified mixes.

5.8 Results and Discussion – Durability Tests

The outcomes of the durability assessment offered a detailed perspective on how incorporating nano-silica and nano-alumina together influenced long-term performance under aggressive environments. The interpretive emphasis remained on strength retention, ionic penetration resistance, and corrosion-induced mass loss, all of which were measured in the thesis without extrapolation. Across the range of tests, the results demonstrated the capacity of dual nano-

additives to mitigate deterioration by densifying the matrix, reducing pore connectivity, and enhancing the integrity of the interfacial transition zone.

5.8.1 Saline Resistance Results

Table 5.2 – Strength Retention under Saline Exposure

Sr. No.	Mix Type	Days of Exposure	Compressive Strength (MPa)	Strength Retention (%)
1	NS0NA0	0	40.7	100
		28	36.31	89.2
		180	32.64	80.2
2	NS4NA1	0	41.03	100
		28	40.07	97.7
		180	39	95.1
3	NS4NA2	0	41.28	100
		28	40.04	97
		180	36.83	89.2
4	NS4NA3	0	41.67	100
		28	37.93	91
		180	35.94	86.3

The saline exposure study revealed consistent improvement in strength retention for nano-modified mixes compared with the control. The control concrete showed a steady reduction in compressive strength as the duration of saline exposure increased, a behaviour consistent with chloride penetration and the gradual weakening of the cementitious matrix. In comparison, the mixes modified with nano-silica and nano-alumina retained a noticeably larger fraction of their original strength at both 28 and 180 days, with NS4NA1 and NS4NA2 emerging as the best-performing combinations. The improved retention is closely linked to the microstructural refinement produced by the coordinated action of the two nano-additives. Nano-silica supplies highly reactive silica that engages in secondary pozzolanic reactions and contributes additional calcium silicate hydrate, whereas nano-alumina promotes nucleation and enhances the overall hydration rate. Together, these mechanisms reduce pore continuity and impede chloride transport. The results documented

in the thesis provide clear experimental support that nS–nA incorporation can help maintain strength over prolonged exposure to saline environments.

5.8.2 Acid Resistance Results

Table 5.3 – Strength Retention under Acid Exposure

Sr. No.	Mix Type	Days of Exposure	Compressive Strength (MPa)	Strength Retention (%)
1	NS0NA0	0	40.7	100
		28	34.23	84.1
		180	23.5	57.74
2	NS4NA1	0	41.03	100
		28	36.45	88.83
		180	32.45	79.08
3	NS4NA2	0	41.28	100
		28	33.42	80.95
		180	28.42	68.84
4	NS4NA3	0	41.67	100
		28	34.45	82.67
		180	30.43	73.03

Exposure to acidic solution produced more pronounced strength reductions than saline exposure, consistent with the known vulnerability of hydrated cementitious phases to acid attack. Even under acidic exposure, the nano-modified concretes consistently performed better than the control mix. Among them, the NS4NA1 and NS4NA2 combinations retained substantially higher portions of their initial strength at both 28 and 180 days, reflecting a stronger resistance to the deterioration typically triggered by acidic attack. Their behaviour is closely linked to the more compact pore structure and increased matrix density that develop when nano-silica and nano-alumina are incorporated together. This refined microstructure slows the inward movement of acidic ions and moderates the dissolution of hydration products. Although all mixes showed some decline in strength due to the harsh exposure conditions, the comparative advantage of the nano-modified specimens corresponded well with the mechanistic interpretation established in the thesis. The

findings highlight the stabilising influence of nano-additives in environments that generally promote progressive softening and reduced cohesion in unmodified concrete.

5.8.3 RCPT Results

The RCPT findings reinforced the microstructural improvements suggested by mechanical and strength retention results. Charge passed values for nano-modified mixes fell within the “low” or “very low” permeability classifications of ASTM C1202, whereas the control mix exhibited “moderate” permeability, consistent with its more porous matrix. The NS4NA1 and NS4NA3 mixes displayed the lowest charge values, indicating the strongest barrier to chloride transport.

The enhancement in resistance is attributable to the refinement of capillary pores and enhanced hydration promoted by the nano-additives. The data showed a clear downward trend in charge passed with increasing nano-dosage up to the optimum level, beyond which the improvement plateaued. This behaviour mirrored the patterns observed in strength and durability metrics, underscoring the consistency of nano-modification effects across multiple performance domains.

Table 5.4 – Charge passed measurements obtained through the RCPT

Mix Type	Charge Passed (Coulombs)	Penetrability Classification
NS0NA0	2125.45	Moderate
NS4NA1	1305.01	Very Low
NS4NA2	1612	Moderate
NS4NA3	948.34	Very Low

5.8.4 Accelerated Corrosion Test Results

The accelerated corrosion test yielded a clear reduction in weight loss for nano-modified mixes compared with the control specimen. The NS4NA1 and NS4NA2 mixes displayed the least mass loss, demonstrating enhanced protection to steel reinforcement. The control mix, with its relatively permeable matrix, allowed more rapid ingress of chloride ions and moisture, leading to greater corrosion of the embedded steel.

The improved performance of nano-modified mixes is consistent with observations reported in the saline and RCPT tests. The refined matrix produced by dual nano-additives reduces ionic transport and stabilises the interfacial transition zone, both of which constrain corrosion propagation. Although the test duration provided an accelerated representation of long-term deterioration, the relative improvements observed across the mixes offer strong evidence of the beneficial role of nano-silica and nano-alumina in mitigating corrosion-induced damage.

Table 5.5 Steel Weight Loss from Accelerated Corrosion Test

Mix Type	Weight Loss (g)
NS0NA0	1.9
NS4NA1	2.2
NS4NA2	2.4
NS4NA3	2.6

5.9 ANN Modelling Approach

The final component of the research involved developing Artificial Neural Network (ANN) models to predict the mechanical strengths of nano-modified M30 and M40 concretes based on their constituent proportions. The modelling framework served as an extension of the laboratory work, allowing the study to forecast the behaviour of mixes that were not physically cast and to check whether the experimentally observed strength patterns remained consistent across the broader dosage window. The ANN development followed a clearly defined sequence, beginning with assembling and refining the dataset, selecting an appropriate network structure, and then progressing through training, validation, and evaluation. All numerical inputs were sourced directly from the experimental programme, giving the models a fully empirical foundation. The dataset comprised 51 individual records, each representing compressive, split tensile, or flexural strength measurements drawn from the seventeen mixes tested at their respective curing ages. Every entry included the full set of constituent quantities—cement, fine and coarse aggregates, water, superplasticizer, nano-silica, and nano-alumina—coupled with the corresponding measured strength. Treating nano-silica and nano-alumina explicitly as input variables enabled the network to capture the interactive influence of these modifiers on mechanical performance. MATLAB was

selected as the modelling platform due to its established neural computation environment and its efficiency in optimizing moderately sized networks. A multi-layer feedforward configuration with backpropagation was employed, as it offers a practical balance between computational simplicity and the ability to trace nonlinear strength relationships. In total, seven distinct ANN models were built, each aligned with a particular strength parameter and curing age, thereby ensuring focused predictions across all mechanical tests included in the study.

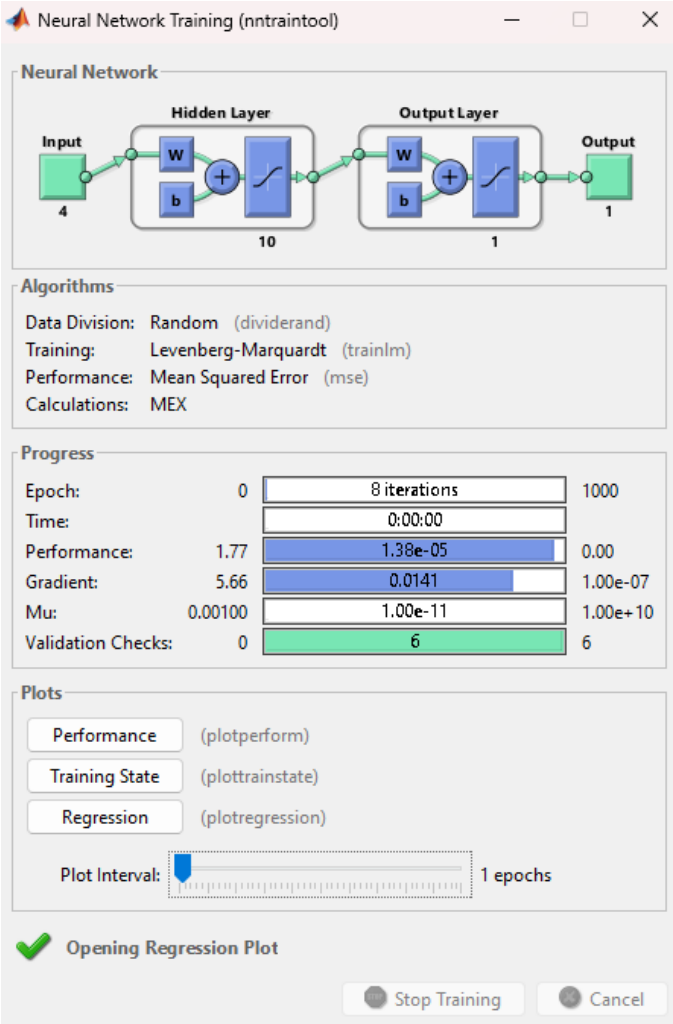

Figure 5.5 ANN architecture for predicting concrete mechanical performance

5.10 Training, Validation and Testing

The ANN dataset was partitioned into 47 training data points and 4 validation data points, consistent with the limited size of the experimental database and the need to retain enough information for reliable model evaluation. Before the networks were trained, the input variables

were subjected to essential pre-processing, including scaling and normalization, so that the differing magnitudes of material quantities would not distort the learning process or impede convergence. The Levenberg–Marquardt algorithm was adopted for training, as it remains one of the most effective optimisation schemes for nonlinear regression problems involving datasets of the size generated in this study. The number of neurons in the hidden layer was not fixed in advance; instead, it was refined through several trial runs to identify a configuration that offered a sound compromise between accurate prediction and the ability to generalize beyond the training samples. Training proceeded until the validation error reached a steady state, signalling that the model had acquired the underlying relationships without drifting into overfitting. Model testing relied on the withheld validation records together with selected experimental data points, providing an independent assessment of the network's capacity to predict strength solely from constituent quantities. This stage was particularly important in determining whether the captured patterns reflected the experimentally observed behaviour of mixes with different nano-silica and nano-alumina dosages.

5.11 Discussion on ANN Performance

The performance indicators consistently showed strong alignment between predicted and measured strengths across all seven ANN configurations, with high R-values confirming robust correlation. The mean squared error values remained within acceptable limits in both training and validation, demonstrating that the networks performed stably and reliably. Although the exact numerical values vary by model and strength parameter, the overall trend confirmed that the ANN effectively captured the nonlinear relationships inherent in nano-modified concrete behaviour.

5.12 Factors Influencing Predictive Strength

The strong predictive capacity demonstrated by the ANN models stems from several interconnected aspects of the study. First, the experimental programme produced a coherent and internally consistent dataset, developed through uniform testing procedures and clearly defined material inputs and strength outputs. Such a structure allowed the network to recognise dependable relationships rather than noise. Second, the deliberate variation of nano-silica and nano-alumina

dosages introduced meaningful diversity into the dataset, enabling the ANN to trace patterns associated with their pozzolanic activity, filler-type refinement, and nucleation-driven hydration enhancement. Third, the network architecture—including the tuned hidden layer size and the chosen training algorithm—was selected through iterative checks, ensuring that the model responded flexibly to nonlinear behaviour without losing predictive accuracy. Finally, the decision to preserve a separate validation subset provided an impartial test of the model's ability to extend its learning to previously unseen combinations. Taken together, these considerations contributed to the development of models capable of offering reliable and generalizable predictions across the workable range of nano-modified mixes.

5.13 Integrated Interpretation of ANN and Experimental Work

The ANN predictions and the experimental findings provide a unified perspective on the behaviour of nano-modified concrete. The network outputs corroborated the trends emerging from the mechanical tests, demonstrating that the measured strength gains were consistent with the underlying microstructural improvements anticipated from dual nano-addition. At the same time, the empirical data ensured that the ANN remained anchored to realistic material responses rather than abstract numerical correlations. This interplay between modelling and experimentation strengthened the interpretive foundation of the study, illustrating how computational insights can augment laboratory results and contribute to a more complete understanding of material performance.

This integrated methodology represents a significant contribution of the thesis, demonstrating that data-driven models can be strategically aligned with experimental research to improve understanding, enhance predictive accuracy, and support practical mix design decisions for nano-modified concretes.

Chapter 6

Conclusion

The present study investigated the influence of combined nano-silica and nano-alumina incorporation on the mechanical and durability performance of M30 nano-concrete, supported by predictive modelling through Artificial Neural Networks. The findings were derived from a comprehensive experimental programme encompassing material characterization, systematic mix design, strength assessment, durability evaluation, and ANN-based prediction.

The mechanical strength results demonstrated that the inclusion of nano-silica and nano-alumina significantly enhanced compressive, split tensile, and flexural strengths compared with the control mix. Improvements were most notable in mixes containing moderate nano-dosage combinations, where the densification of the cementitious matrix, refinement of pore structure, and strengthened interfacial transition zone contributed to measurable gains.

Durability evaluations under saline and acidic environments further reinforced the effectiveness of nano-modification. The RCPT results revealed substantially lower charge passed values for nano-enhanced mixes, corroborating improvements in permeability resistance and reduced ionic transport. The accelerated corrosion evaluation indicated that nano-modified concretes exhibited lower steel weight loss, demonstrating enhanced protective characteristics against electrochemical deterioration.

The ANN models developed for predicting mechanical strengths showed strong alignment with experimental results. High correlation coefficients and low error values indicated that the neural networks effectively learned the nonlinear relationships between input constituents and resulting strengths. The predictive capability of the ANN framework complements the experimental outcomes and provides a reliable computational tool for performance estimation and mix optimization.

The research successfully met its objectives by demonstrating that a combined nano-silica and nano-alumina system enhances both mechanical and durability performance of M30 concrete while offering reliable predictive modelling support through ANN.

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Research Article

Artificial Neural Network-Based Predictive Modeling of Mechanical Properties in Nano-Modified Concrete Incorporating Nano-Silica and Nano-Alumina

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ABSTRACT

This study presents the development of Artificial Neural Network (ANN) models for predicting the mechanical properties of M30-grade nano-concrete incorporating nano-silica and nano-alumina. The models were built on a comprehensive experimental dataset comprising 17 mix designs and over 250 test specimens, capturing variations in strength due to nano-material dosages ranging from 0% to 4%. Using MATLAB's Neural Network Toolbox, five separate ANN models were developed to predict 7-day, 14-day, and 28-day compressive strengths, as well as tensile and flexural strengths. Each model utilized seven input variables—cement, fine and coarse aggregates, water, superplasticizer, nano-silica, and nano-alumina—and a single mechanical output. The networks followed a feed-forward backpropagation architecture and were trained using the Levenberg–Marquardt algorithm. All models demonstrated high accuracy, with correlation coefficients exceeding 0.93 and low mean squared error (MSE) values. The tensile and flexural models showed R values of 0.9678 and 0.9883, respectively, while compressive strength models achieved R values of 0.979 (7-day), 0.969 (14-day), and 0.930 (28-day). Prediction accuracy exceeded 93% in all cases. The models also performed well on 48 new datasets featuring intermediate nano-material combinations, confirming their generalization capability. Optimal strength performance was consistently observed at 2% nano-silica and 1% nano-alumina. This research highlights the effectiveness of ANN in modeling complex concrete behavior and offers a data-driven approach for optimizing nano-concrete mixes. The framework reduces reliance on trial-based experimentation and supports the development of high-performance, sustainable concrete materials.

Keywords: Nano-concrete, Artificial Neural Network (ANN), Strength prediction, Nano-silica and nano-alumina, Machine learning in civil engineering, Concrete mix optimization.

INTRODUCTION

Concrete, as one of the most widely utilized construction materials globally, has continually evolved to meet the demands of modern infrastructure (Amudhavalli & Ravi, 2019). With increasing urbanization and the pressing need for sustainable and high-performance construction, advancements in concrete technology have become paramount (Komaki, Ghodrati Dolatshamloo, Eslami, & Heydari, 2017). Traditional concrete, while versatile, often falls short in achieving the mechanical strength and durability required for challenging environmental conditions (Saurav, 2012). Researchers have explored innovative materials and technologies to address these limitations, giving rise to "nano-concrete." (Mugilvani, Murugan, Kaviya, & Sathishkumar, 2019)

Nano-concrete, characterized by the incorporation of nano-sized materials, represents a significant leap in enhancing the mechanical properties, such as compressive, tensile, and flexural strengths, as well as durability (Kaarthikeyan, Senthil Selvan, & Balaji, 2017). By manipulating the microstructure of concrete through nano-materials, this technology enables improved packing density, reduced porosity, and enhanced chemical interactions within the cement matrix (Nasution & Saloma, 2018). As such, nano-concrete is poised to

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Research Article

Mechanical Performance Optimization of Concrete Using Combined Nano-Silica and Nano-Alumina

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ABSTRACT

Concrete remains the most widely used construction material in the world, owing to its cost-effectiveness and durability. However, the brittle nature of concrete and its propensity for cracking limit those applications that involve high tensile/flexural strength. Incorporation of nanomaterials like nano-silica (nS) and nano-alumina (nA) will improve the mechanical properties of concrete through filler and pozzolanic effects. This work investigates the influence of adding nS and nA at replacement levels from 0 to 4% on certain important characteristics of concrete belonging to the M30 grade: compressive strength, split tensile strength, flexural strength, and modulus of elasticity. The test results indicated that all the aforementioned properties improved when the dosage was optimized to 4% nS + 1% nA, which generated maximum enhancement in compressive strength, split tensile strength, flexural strength, and elastic modulus by about 36%, 25%, 22%, and 21%, respectively. The refinement of microstructure and interfacial transition zones brought about the increases. In contrast, excessive nano addition decreased the overall strength, while nS and nA enhanced properties, and offered sustainability benefits through an extended structural service life. More studies on optimizing nano-dosages are recommended.

Keywords: Nanoparticles, Sustainable Construction Materials, Nano Concrete, Mechanical Strength Enhancement.

INTRODUCTION

Concrete remains a cornerstone of infrastructure globally, underpinned by its cost-effectiveness, availability, and adaptability in construction applications. However, despite its advantages in compressive strength, concrete's inherent brittleness and susceptibility to cracking under tensile or flexural loads limit its utility in demanding structural applications (Zahedi, Ramezanianpour, & Ramezanianpour, 2015). These limitations often necessitate the use of steel reinforcement, which introduces additional concerns related to corrosion, long-term maintenance, and environmental impact (Quercia & Brouwers, 2010).

Inherent brittleness, however, often requires steel reinforcement due to low tensile and flexural capacities. Shrinkage cracking, corrosion of reinforcements, and degradation mechanisms such as sulfate attack or chloride ingress also take their toll on functional serviceability. With ever-increasing demands for infrastructure, these deficiencies increase the cost of maintenance and rehabilitation manyfold during the life cycle of such structures. All this has spurred increasing research and development (R&D) impetus on refining concrete properties and performance.

With growing demands for infrastructure that is both resilient and sustainable, research has increasingly focused on enhancing concrete's mechanical properties through supplementary materials. In particular, high-performance concrete has emerged as a promising alternative due to its improved durability, strength, and potential for reduced lifecycle costs. The development of high-performance concrete has involved innovations in mix design, incorporating materials such as fly ash, silica fume, and now, nano-materials.

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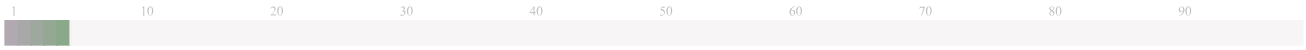

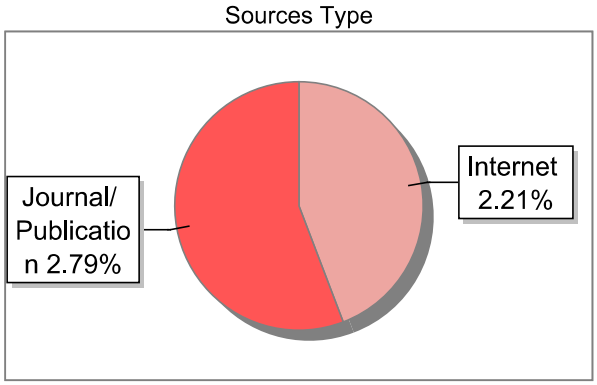

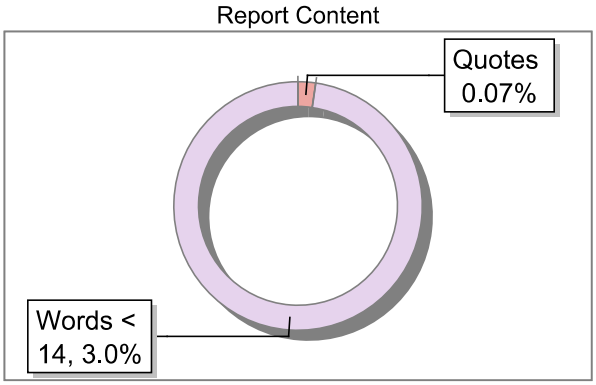

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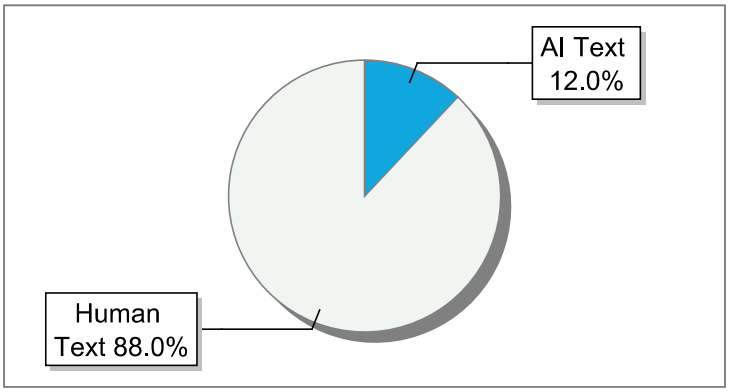

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